CONTROL AND STARTUP
CONSIDERATIONS FOR TWO-SPOOL
SOLAR-BRAYTON POWER SYSTEM

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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SUMMARY

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An analog computer simulation of a two-spool solar Brayton system was used to study the control requirements of this system for operation in a 300-nautical-mile ecliptic Earth orbit. Startup in orbit by means of injecting the gas inventory into the initially evacuated system was also investigated. The simulated system uses a radial-flow turbocompressor and an axial-flow alternator - drive turbine with a power output of 10 kilowatts at design conditions. The working gas is argon, and the heat storage medium for shade operation is lithium fluoride.

The results of the study indicate that an overtemperature control for the heat storage component is required in addition to the solar-collector-orientation control and the turbo-alternator speed, voltage, and overload controls. Closed-system, gas-injection startups can be accomplished by directing cold gas into the absorber by using a check valve to prevent reverse flow, or by injecting hot gas (1250° R) at the inlet of the compressor-drive turbine without a check valve. Overdesign power usage from the heat storage component during startup with a cold radiator can be accommodated by starting during specific periods of the orbit.

Author

INTRODUCTION

An investigation is being conducted by the NASA Lewis Research Center to determine the practicality of developing a solar Brayton system for space electric power generation. The system being investigated uses a parabolic mirror, called a collector, to focus solar energy into the aperture of a heat-storage, heat-exchanger component referred to as an absorber. The heat storage is accomplished by the melting of lithium fluoride contained in the absorber. Heat transfer is from the absorber to the argon working gas of the Brayton cycle. In the two-spool system, the hot gas drives two turbines; the first

turbine drives the compressor, and the second turbine, with a design output of 10 kilowatts, powers the alternator. The closed Brayton cycle also includes a recuperator and a waste heat rejection system. Some characteristics displayed by Brayton cycles for space power are discussed in references 1 and 2.

Part of the solar Brayton investigation is concerned with defining the control and startup requirements of the system in a 300-nautical-mile ecliptic Earth orbit. For this purpose, an analog computer simulation is being used to study the sensitivities of the solar Brayton system to various disturbances and to study the transients imposed by various startup schemes. From these studies, the control requirements for long-term orbital operation are being analyzed, and the preferred startup procedures are being determined. This report is a brief presentation of the information obtained thus far.

CONTROL REQUIREMENTS FOR OPERATION AFTER STARTUP

Description of System

A schematic diagram of the solar Brayton system studied is shown in figure 1. The sun period of a 300-nautical-mile ecliptic Earth orbit is the environmental condition of the system design point. The design values of argon flow and the pressures and temperatures throughout the system for the in-sun condition are indicated in the diagram. The system employs a radial-flow turbocompressor with a design speed of 38 500 rpm and an
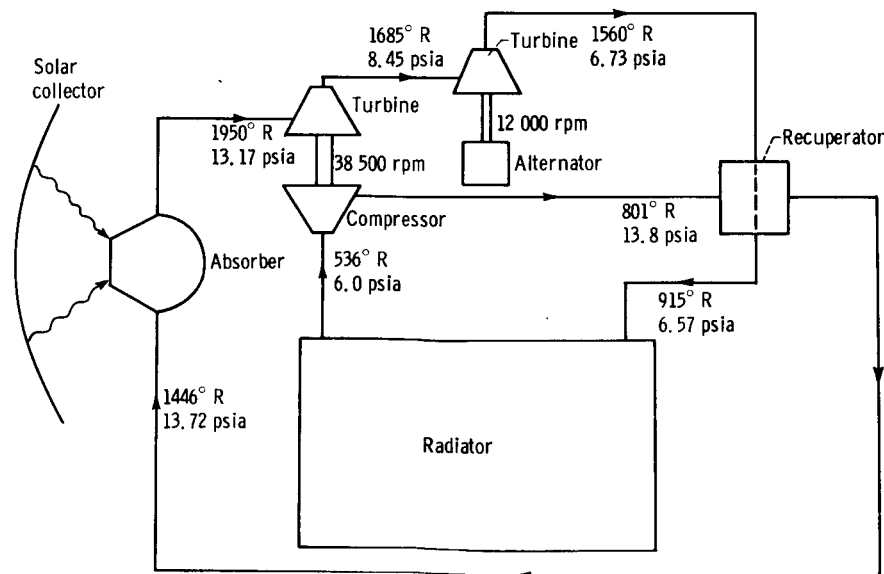
Figure 1. - Schematic diagram of two-spool solar Brayton system showing design conditions (in Sun) of pressure, temperature, and flow. Argon gas flow, 0.611 pound per second.

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axial-flow alternator-drive turbine with speed controlled at 12 000 rpm and a power output of 10 kilowatts at design conditions. Both rotating units operate on gas bearings. The power transferred from the absorber to the gas is 40 kilowatts at the design condition; the gross power input from the collector to the absorber is assumed to be 67.9 kilowatts and the net power 65.2 kilowats. (The difference of 2.7 kW is lost by radiation through the aperture.) It is also assumed, of course, that there is sufficient lithium fluoride in the absorber to store the energy resulting from the 25.2 kilowatts of excess power during the 60.5-minute sun period. This stored energy provides for the 35.5-minute shade period during which energy is consumed by the gas system at about a 40-kilowatt rate and is lost through the aperture at a 2.7-kilowatt rate. As shown in figure 1, a direct gas-flow radiator was used in the study; however, the results are applicable, in general, to a system with heat rejection to a liquid flow radiator loop.

Computer Simulation

The analog computer simulation consists of component programs integrated into a complete system simulation. For simulation of the pressure-flow dynamics, the system is lumped into five volumes with each volume connected by a resistance. Three of the resistances are the two turbines and the compressor, while the other two resistances represent the pressure drops of the heat-transfer equipment.

The two turbines and the compressor are simulated by three-variable performance maps from which the torques are continuously calculated. The speed of each rotating unit is determined continuously from these torques and the appropriate inertias. Estimated bearing losses were included in the torque map of the turbocompressor.

The radiator simulation consists of steady-state maps and transfer functions representing the dynamics of the output temperature to changes in the inlet temperature, flow rate, and sink temperature. The transfer functions were obtained from a separate study by using a dynamic 10-lump radiator simulation. A constant radiating area was used throughout the study.

For complete system studies, the absorber is simulated by assuming that the temperature of the lithium fluoride is always at the melting point. This assumption was dropped when the collector-absorber subsystem was studied. In the recuperator simulation the variation of effectiveness with flow rate is included.

Sensitivities of Uncontrolled Brayton Loop

Studies were made of the uncontrolled system to determine the control requirements

(a) Absorber-output power.

(b) Alternator – drive-turbine power.

(c) Compressor speed.

(d) System flow rate.
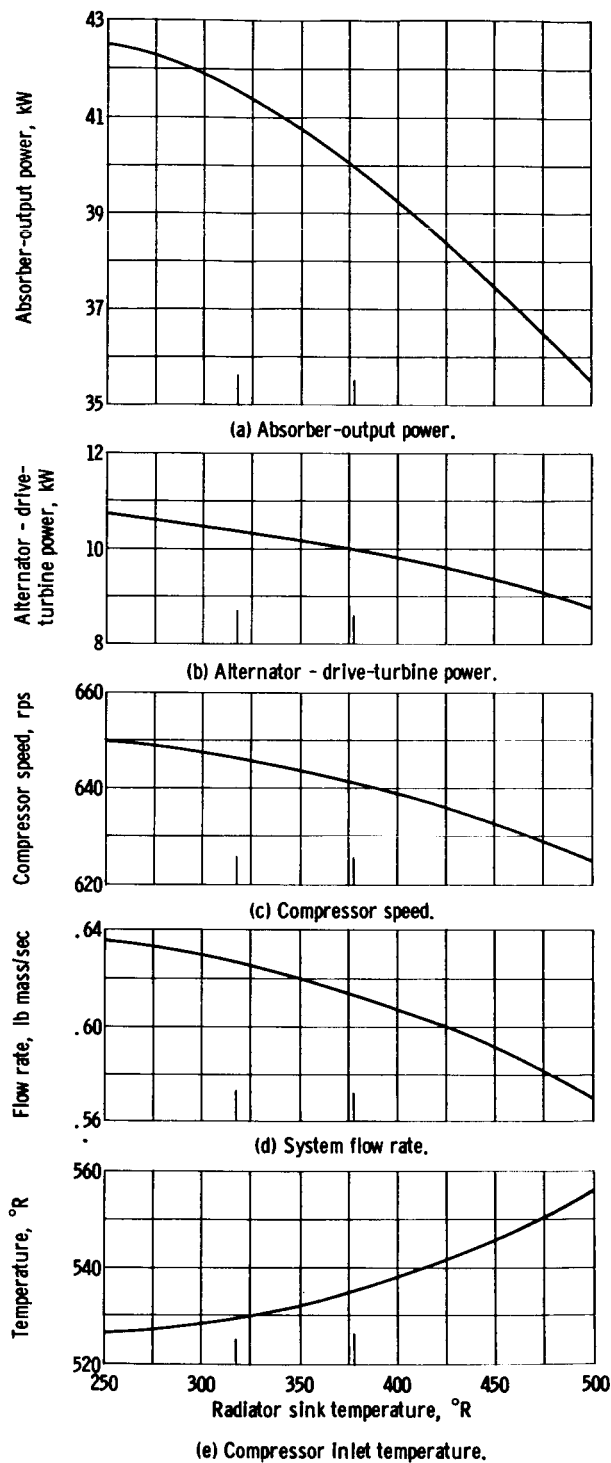
(e) Compressor inlet temperature.

Figure 2. – System variables as function of radiator sink temperature. Minimum shade temperature for 300-nautical-mile ecliptic Earth orbit, 317° R; maximum Sun temperature for 300-nautical-mile ecliptic Earth orbit, 377° R.
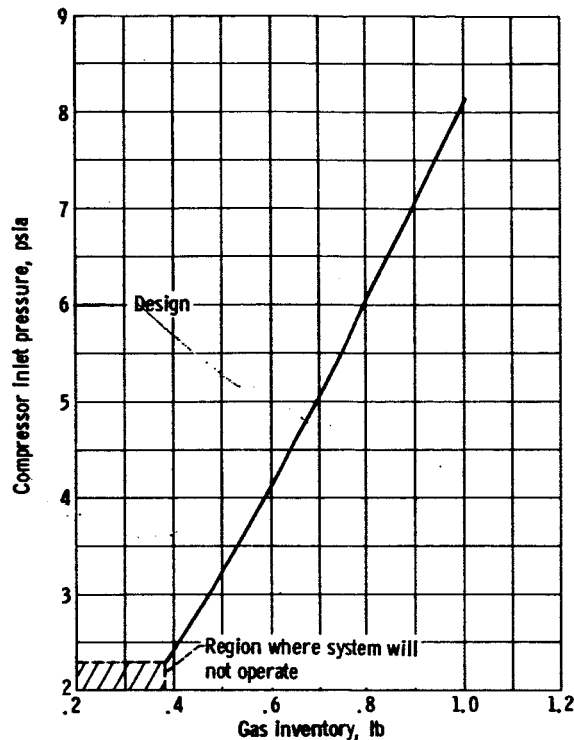
Figure 3. - Variation of compressor inlet pressure with gas inventory.

in addition to the obvious requirements of speed and voltage control of the turboalternator, and orientation control of the collector. The resulting sensitivities are summarized first, and then implications regarding control are discussed.

The effect on the system of radiator sink temperature changes resulting from sun-to-shade operation in a 300-nautical-mile ecliptic Earth orbit is small (fig. 2). As effective sink temperature changes from 377° to 317° R (sun to shade), absorber output power increases 4 percent, alternator - drive turbine power, 4 percent, and compressor speed, 1 percent.

The effect of gas inventory on system performance is shown in figures 3 and 4. Since system volumes are likely to change as system studies progress, the variation of system variables with compressor inlet pressure (fig. 4) is more meaningful than the variation of system variables with gas inventory. As shown in figures 3 and 4, the effect of gas inventory on alternator - drive-turbine power, absorber-output power, and turbocompressor speed near the design point is small. A 1-percent change in gas inventory results in only a 0.1-percent change in alternator - drive-turbine power, a 0.5-percent change in absorber-output power, and a 0.2-percent change in turbocompressor speed. The minimum inventory for the operation of the system was 47.5 percent of design inventory. Below this value of inventory, there was no stable intersection of the closed-system, torque-speed curves of the compressor and its turbine.
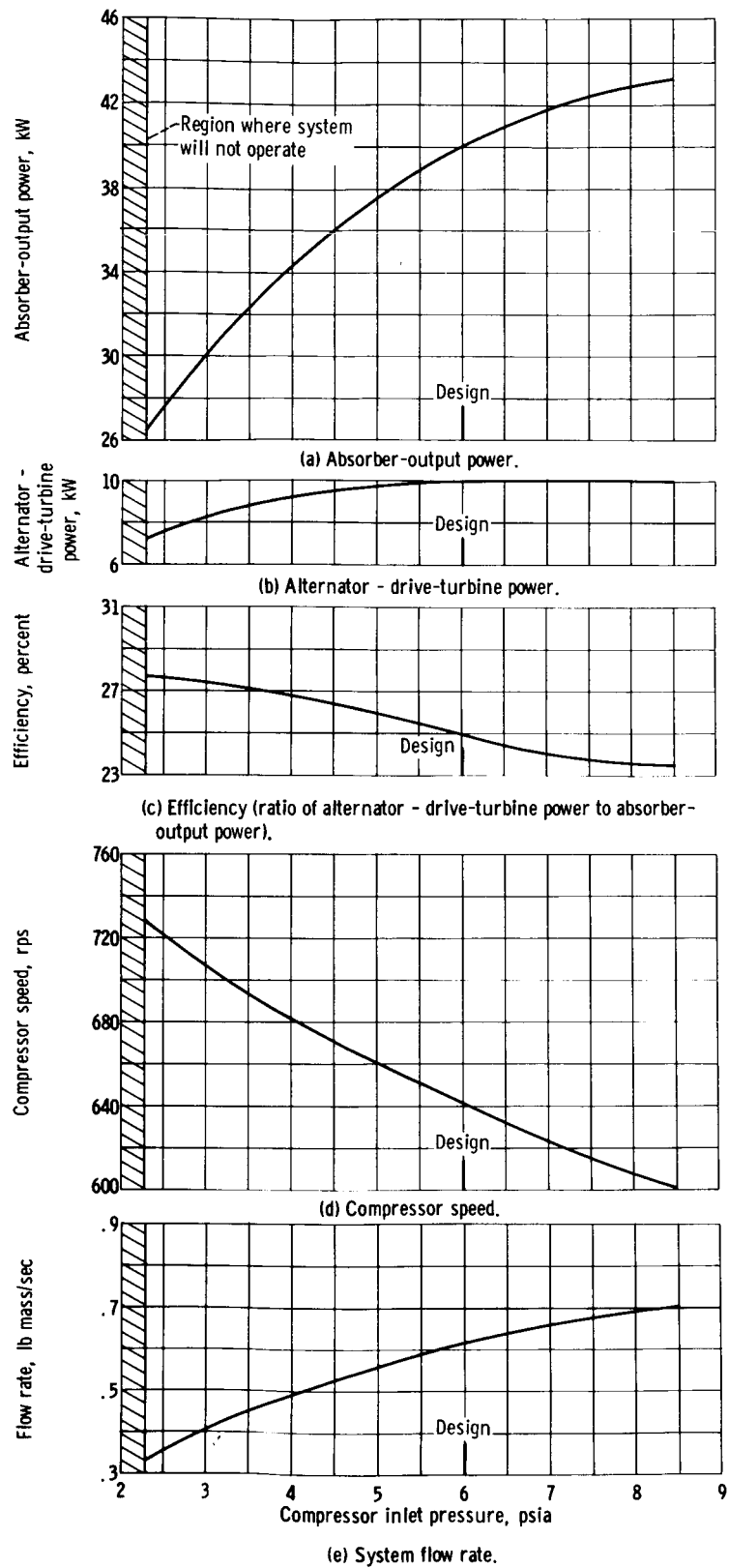
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(a) Absorber-output power.

(b) Alternator - drive-turbine power.

(c) Efficiency (ratio of alternator – drive-turbine power to absorber-output power).

(d) Compressor speed.

(e) System flow rate.

Figure 4. – System variables as function of compressor inlet pressure.

(a) System flow rate.

(b) Compressor speed.

(c) Absorber-output power and alternator - drive-turbine power.
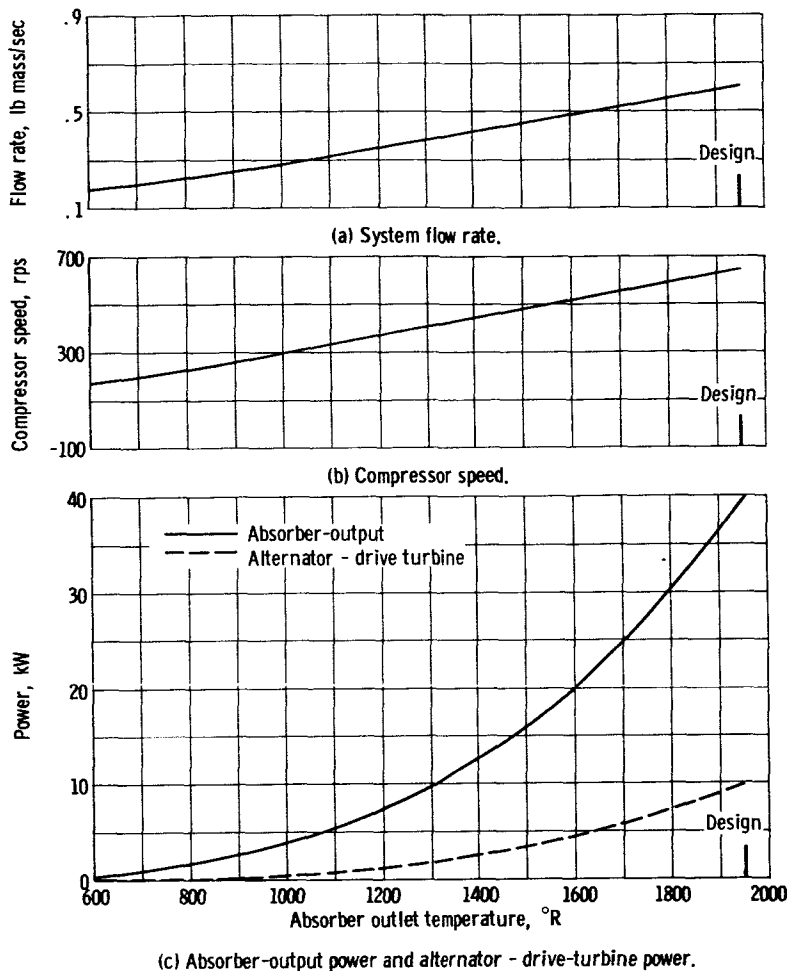
Figure 5. - System variables as function of absorber-outlet temperature.

Studies were made to determine the effect of below-design power input to the absorber from the collector. Below-design collector power, of course, could result from design uncertainties, collector degradation or damage, or orientation-control malfunction. With a sufficient reduction in collector power, the lithium fluoride will eventually solidify and enter its sensible heat region, and lower gas inlet temperature to the compressor - drive turbine will result. The effect of this lower turbine-inlet temperature (absorber-gas outlet temperature) on system performance is shown in figure 5. The simulated system continued to operate with temperatures approaching 600° R; however, the simulation of turbocompressor bearing losses was approximate and this minimum temperature is, in the same sense, approximate. The variation of absorber characteristics with gross collector power for a 300-nautical-mile ecliptic Earth orbit is shown in figure 6. The curves represent equilibrium conditions, which are achieved in about three orbits. The maximum and minimum absorber-gas outlet temperature and the

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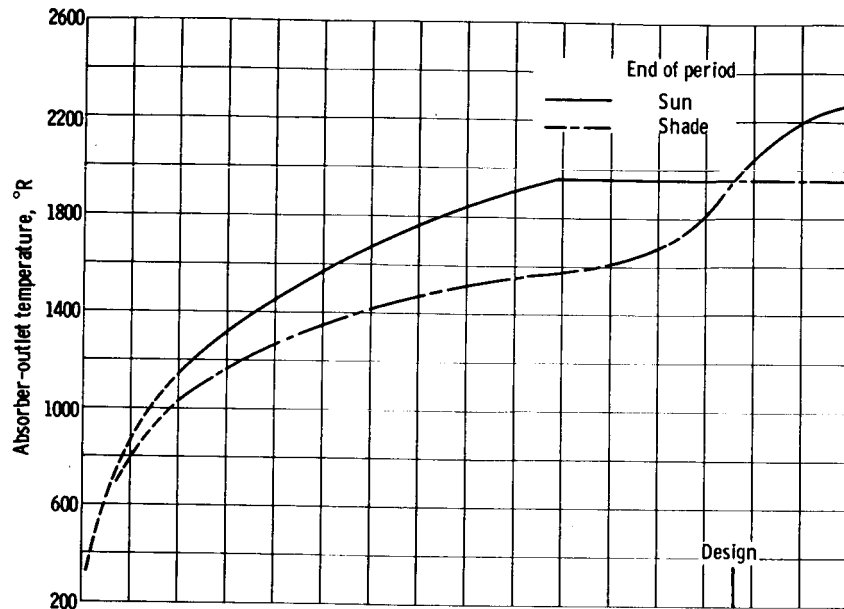
(a) Outlet temperature.
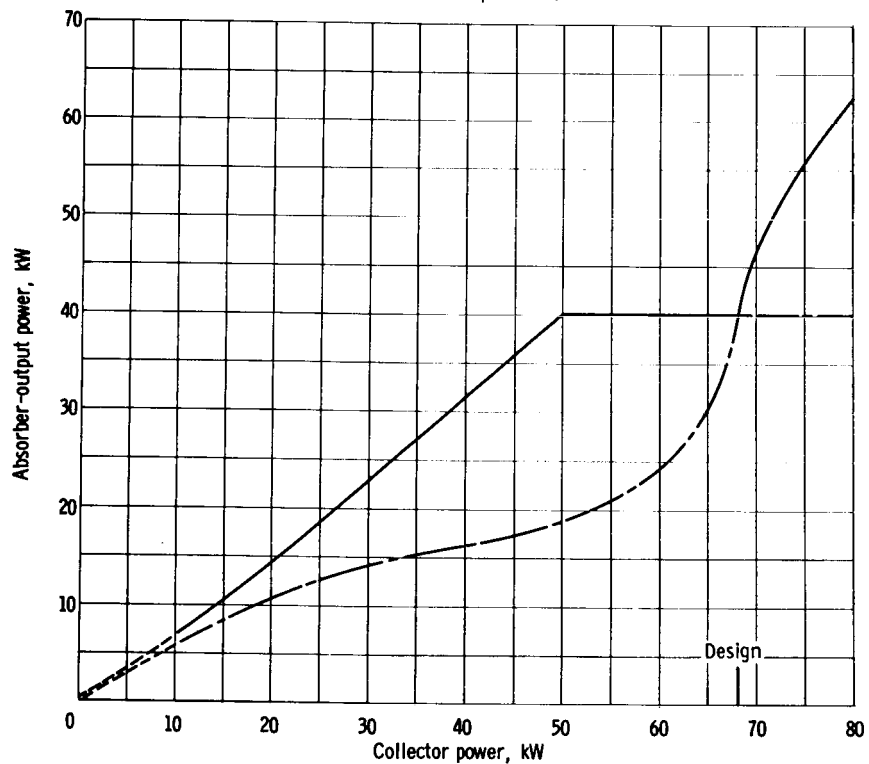
(b) Absorber-output power.

Figure 6. - Variation of absorber operation with gross collector power input to absorber. Curves represent equilibrium condition after several revolutions in 300-nautical-mile ecliptic Earth orbit.

maximum and minimum power output from the absorber to the gas system are shown as functions of collector power in figures 6(a) and (b), respectively. For a particular collector power, the minimum absorber-outlet temperature or power occurs at the end of the shade period, and the maximum power or temperature occurs at the end of the sun period.

Control Implications

The sink temperature and gas inventory studies summarized previously show that the variations in alternator - drive-turbine power above design from these effects are small enough to be provided for in the speed control design. If gas inventory is reduced below design, alternator - drive-turbine power will be reduced by a small amount; if collector power input to the absorber is appreciably reduced from its design value, it will also be reduced during a portion of the orbit. If the load is greater than the available driving power, the turboalternator speed control will not be able to prevent speed decay. Small reductions in turbine power, of course, are normally provided for by the design margin between turbine power and load. In order to provide for larger reductions in turbine power, such as may result from collector degradation, a control is needed to remove load. This overload control should be devised to remove the load in a priority manner, with the least important loads removed first.

Turbocompressor speed was shown to vary only 1 percent during sun-shade operation and only 0.2 percent for a 1-percent change in gas inventory. These small variations indicate that a turbocompressor speed control is not needed.

The absorber output power increased 4 percent during shade operation and changed 0.5 percent for 1-percent changes in inventory. These changes are not large enough to require any special absorber power control. Attention, of course, will be given to these effects in the final matching of the power system to a given collector-absorber combination in order to provide sufficient operating margin in regard to complete freezing of the lithium fluoride. The matching assumed for the study (40 kW absorber power for 65.2 kW net collector power) provided no appreciable margin.

Collector power input to the absorber has quite a large effect on absorber and system operation. If the collector power achieved in a mission is above the value required to obtain completely molten lithium fluoride, the lithium fluoride temperature and the absorber-cavity temperature will increase. Because of mechanical problems associated with overtemperature in the absorber, an overtemperature control must be provided. This control is discussed in the section Control Methods.

If the collector power input to the absorber is reduced from the design value (or if the absorber-output power is above design), premature freezing of the lithium fluoride
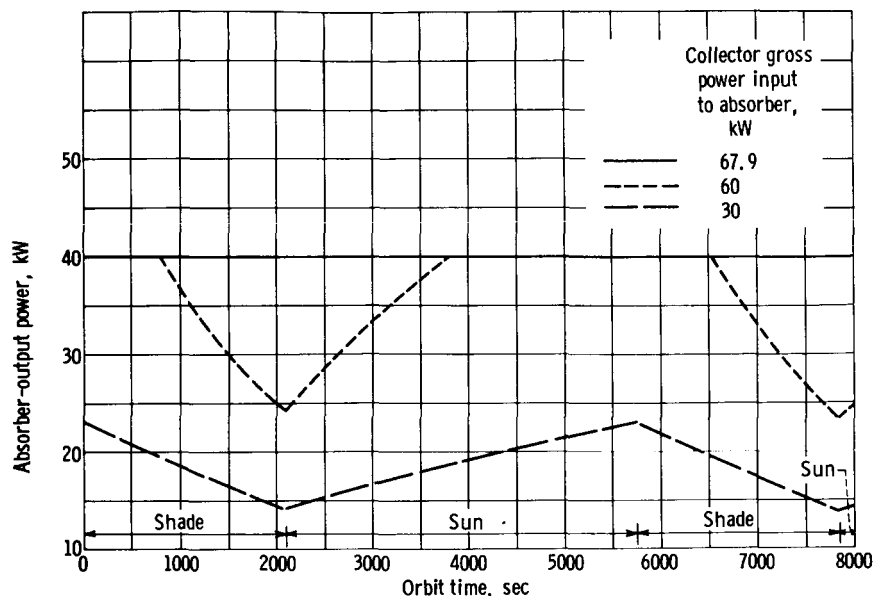
Figure 7. - Absorber-output power for different collector powers as function of orbit time in 300-nautical-mile ecliptic Earth orbit.

during the shade period may result. Operating in the lower sensible heat region of the lithium fluoride results in absorber and alternator - drive-turbine power variations, as were shown in figures 5 and 6. Figure 7 shows absorber-output power plotted against orbit time for different values of collector power. The curves are for the equilibrium condition reached after three orbits in a 300-nautical-mile ecliptic path. Because reduced collector power has such a large effect on absorber-output power and consequently, turboalternator power, it is evident that a system with an absorber-output-power control would have some advantages over a system without such a control. Methods for this control are discussed in the next section.

Control Methods

Absorber-output power control. - A comparison is shown in figure 8 of alternator - drive-turbine power with and without absorber-output-power control for various collector powers. For the uncontrolled system, figure 8 shows the maximum and minimum values between which the alternator - drive-turbine power cycles during each orbit. The other curves show alternator - drive-turbine power for two different methods of absorber output power control. One method uses inventory adjustment, while the other method uses a bypass loop from compressor outlet to inlet. The compressor outlet-to-inlet bypass loop (fig. 9) was the most effective of several studied; that is, it had the highest gain and the largest range of control (fig. 10). For both control methods of figure 8, operation of
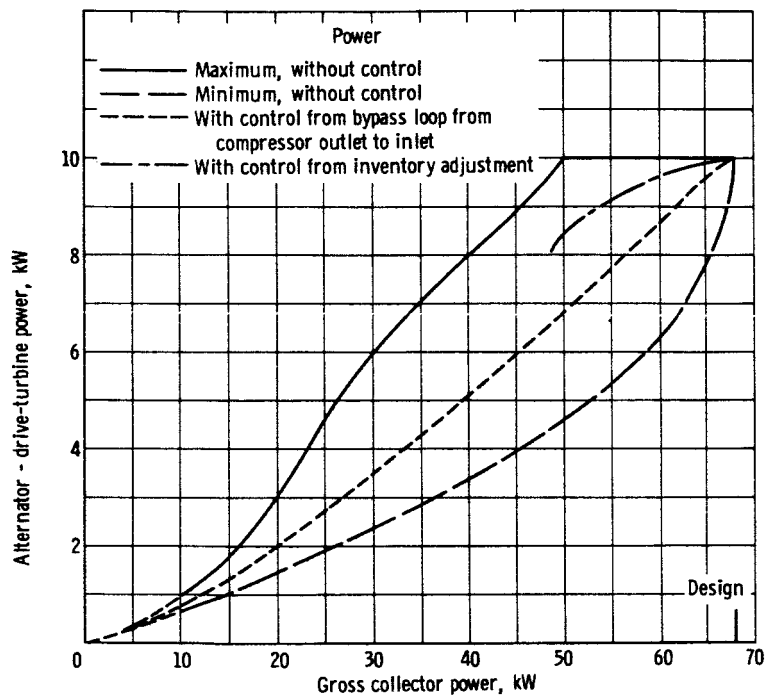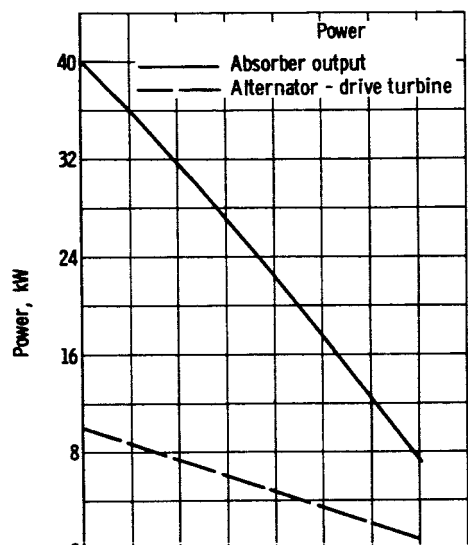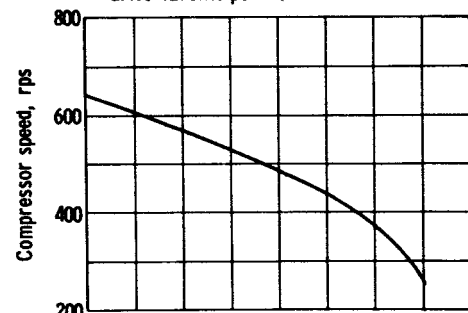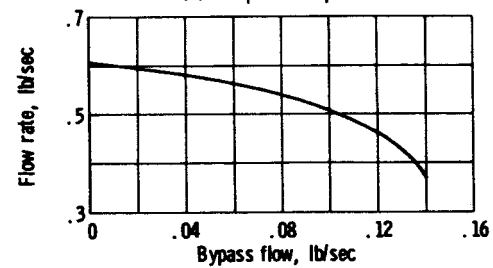
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Figure 8. - Alternator - drive-turbine power as function of collector power with and without control of absorber-output power.

(a) Absorber-output power and alternator - drive-turbine power.

(b) Compressor speed.

(c) Compressor flow rate.

Figure 9. - System variables as function of loop bypass flow from compressor outlet to compressor inlet.
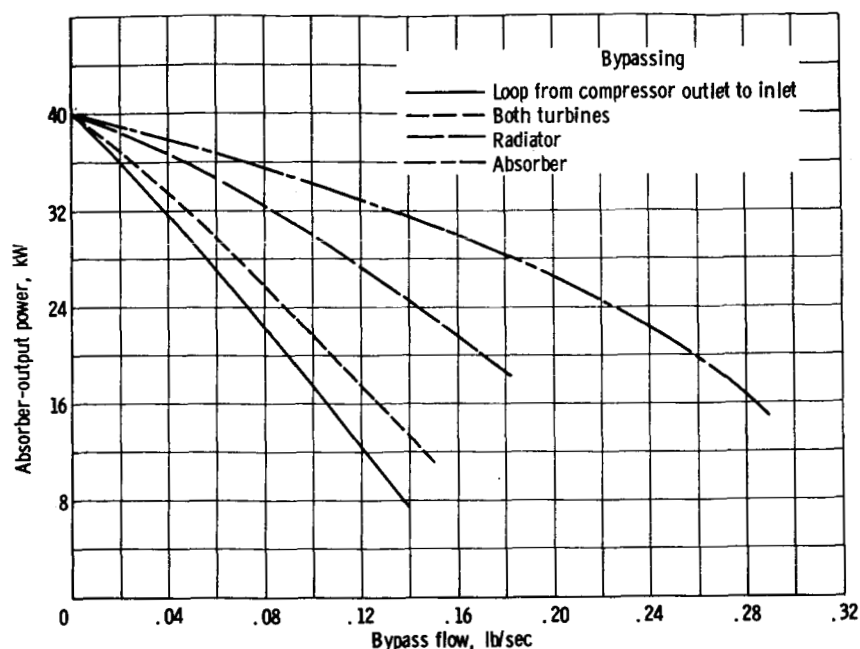
Figure 10. - Sensitivity of absorber output power to bypass flow for various bypass loops.

the absorber was maintained in the latent heat region of the lithium fluoride, and thus constant alternator - drive-turbine power (less than design power) was provided at reduced collector power. As indicated in figure 8, the inventory-adjustment method has a more limited control range than does the bypass loop from compressor outlet to inlet. The simulated system would not operate with inventories below 47.5 percent of the design value; therefore, the range of the inventory method is limited to a reduction in collector power of approximately 25 percent. Within its range of operation, however, the inventory-adjustment method maintains alternator power considerably higher than does the bypass method. Inventory adjustment, therefore, is the preferred method for the relatively small reductions in collector power from the design value that may result from collector degradation or design uncertainties. The bypass method provides a means of control if larger reductions are anticipated, such as could occur from collector damage or malfunction of the orientation control. For both methods, it is necessary to have a continuous signal indicative of the melt condition of the lithium fluoride in order to maintain operation in the latent heat region. There are at least three measurements which could provide such a control signal: (1) the pressure of a cover gas in the lithium fluoride chamber, (2) an average shell temperature of the absorber, and (3) the temperature difference across the lithium fluoride at the absorber gas inlet.

Control of absorber output power can be accomplished more simply by an on-off control operating from a measurement of absorber outlet gas temperature. An appreciable reduction in this temperature indicates that the lithium fluoride is completely frozen. When this signal is received, the control acts in the following manner: The

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(a) Absorber-output power.
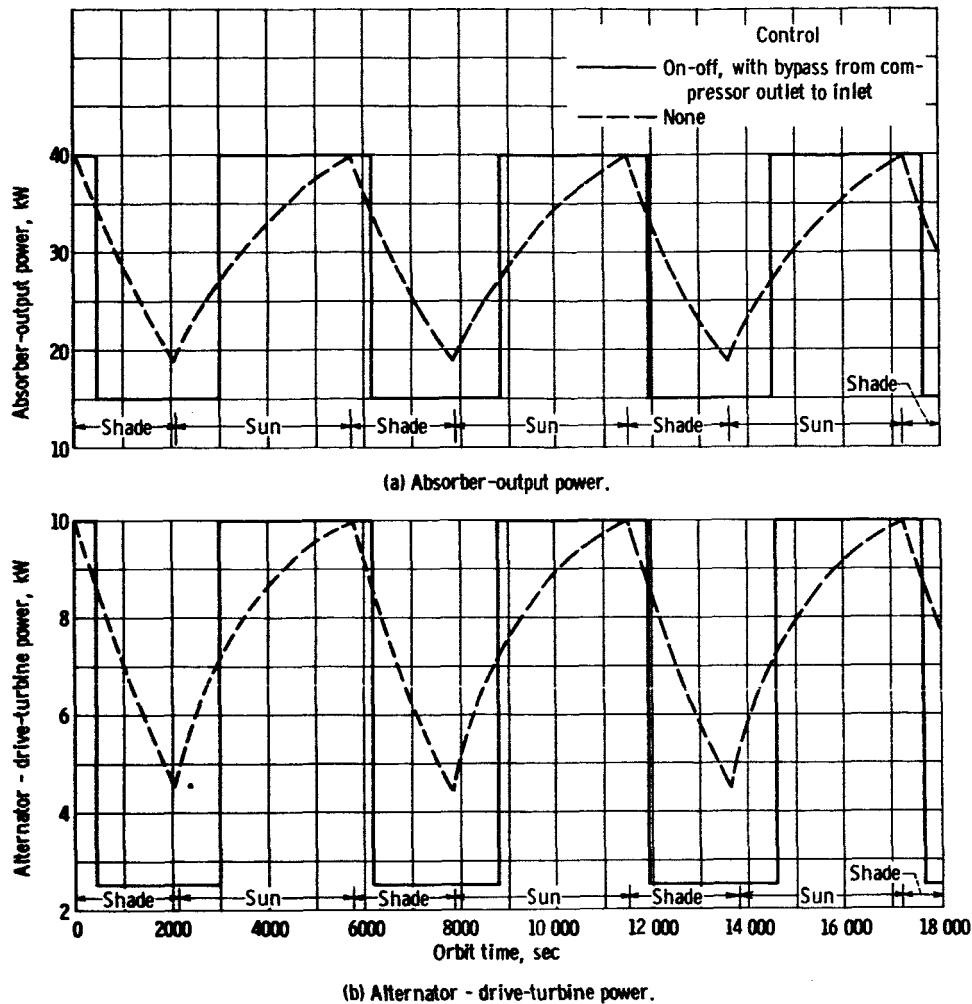

(b) Alternator - drive-turbine power.

Figure 11. - Comparison of on-off control of absorber-output power with no control for 50-kilowatt gross collector power in 300-nautical-mile ecliptic Earth orbit.

absorber output power is reduced by the bypass loop around the compressor to the lowest value that safely meets the operating requirements of the turbocompressor. This minimum power level is maintained until the gas temperature returns to a value associated with melting lithium fluoride. At that time, the bypass valve is closed and full power operation reinstated. Although this control is relatively simple, it provides for either minimum power or full power rather than a modulated constant power level.

A comparison is made in figure 11 of absorber output powers and alternator - drive-turbine powers with no control and on-off control for three orbits in a 300-nautical-mile ecliptic path with 50-kilowatt input from the collector. (Design gross input is 67.9 kW.) With no control, the alternator - drive-turbine power is continuously changing between 10 and 4.5 kilowatts during each orbit, while for an on-off control, the power cycles between 10 and 2.5 kilowatts during each orbit, but remains at 10 kilowatts for a considerable time. The type of absorber control, if any, should be selected on the basis of

the type of mission for which the power system is intended.

Absorber overtemperature control. - As mentioned previously, a control is needed to prevent absorber overtemperature, since an increase in cavity temperature will weaken the absorber and, thus cause mechanical failure. To prevent overtemperature, doors should be provided to radiate excess heat from the absorber cavity. If the gas system is taking design power (40 kW) from the absorber, a door area of 2.4 square feet is required for cavity temperature control. This opening is necessary to provide radiation of 25.2 kilowatts of power if the lithium fluoride melts completely during a sun period. (Net input power from the collector is 65.2 kW.) If the gas system requires less than design power from the absorber, a larger door area is required. An area of about 7 square feet is necessary if the gas system power is zero. For shutdown and re-start capability, of course, the 7-square-foot area is required, unless the solar collector is misoriented or shaded.

STARTUP

With the analog computer simulation, studies were made of gas injection startups. Two different injection points were studied. For each, injection into an initially evac-uated system was simulated at a rate of 10 percent of the design flow. The first point of injection was at the recuperator inlet (cold side), and, in order to prevent flow in the wrong direction, a check valve was simulated in the duct between the injection point and and the compressor outlet (fig. 12). A vent-to-space valve was provided between the
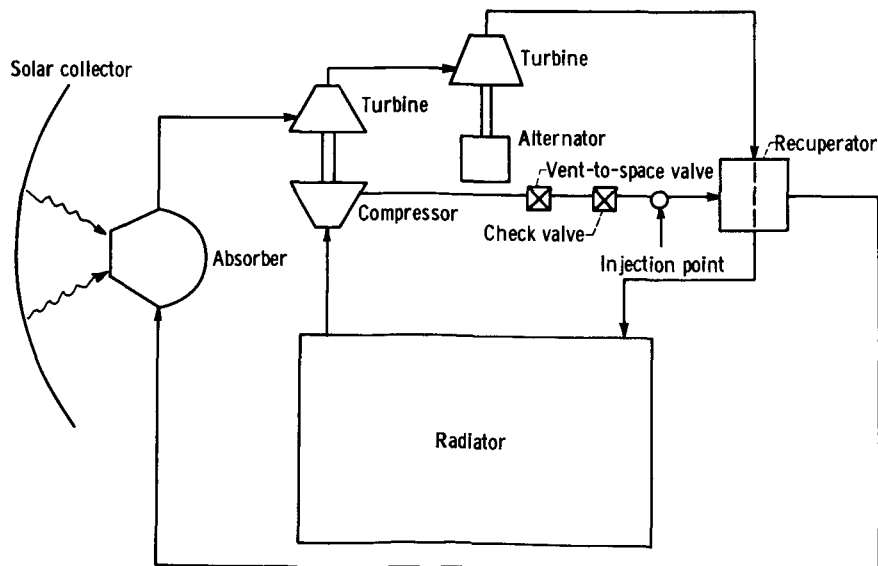

Figure 12. - Schematic diagram of two-spool solar Brayton system showing simulated gas injection point and valves for first startup study.

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compressor outlet and the check valve to maintain low exit pressure for the turbines. From the studies made, however, it was found that, with the large volume of the gas radiator, the vent-to-space valve was not needed for successful startups. The second injection point was at the inlet of the compressor - drive turbine. With this injection point, startup was accomplished without the check valve or vent valve; however, the injected gas temperature had to be at least 1250° R or higher, whereas cold gas injection was sufficient for the first injection point. For both types of startup, the temperature of the lithium fluoride in the absorber was held constant at the melting value (2020° R), and the initial temperature of the radiator metal was 480° R. The accelerations of the turbomachinery during the first type of startup are shown in figure 13.

Calculations were made to determine the effect of a colder initial radiator temperature than that of figure 13. These calculations showed that, if startup is initiated with the radiator cooled to its effective shade sink temperature of 317° R, the alternator - drive-turbine power reaches 18 kilowatts and the absorber output power reaches 58 kilowatts during the startup transient. Unless compressor inlet temperature or absorber-output power is controlled during startup, this overpower requires the parasitic load for the turboalternator speed control to be large enough to consume 18 kilowatts. It also requires the startup to take place during special periods of the orbit to maintain the lithium fluoride in the melt region since the collector-absorber is sized for approximately a 40-kilowatt output power. From power balance calculations of the 60.5-minute sun time of the 300-nautical-mile ecliptic Earth orbit, two startup sequences that satisfy this requirement were determined.

For the first sequence, the lithium fluoride in the absorber is assumed to be at the melting temperature, but with no appreciable quantity melted, when the system enters the sun period

(a) Speed.

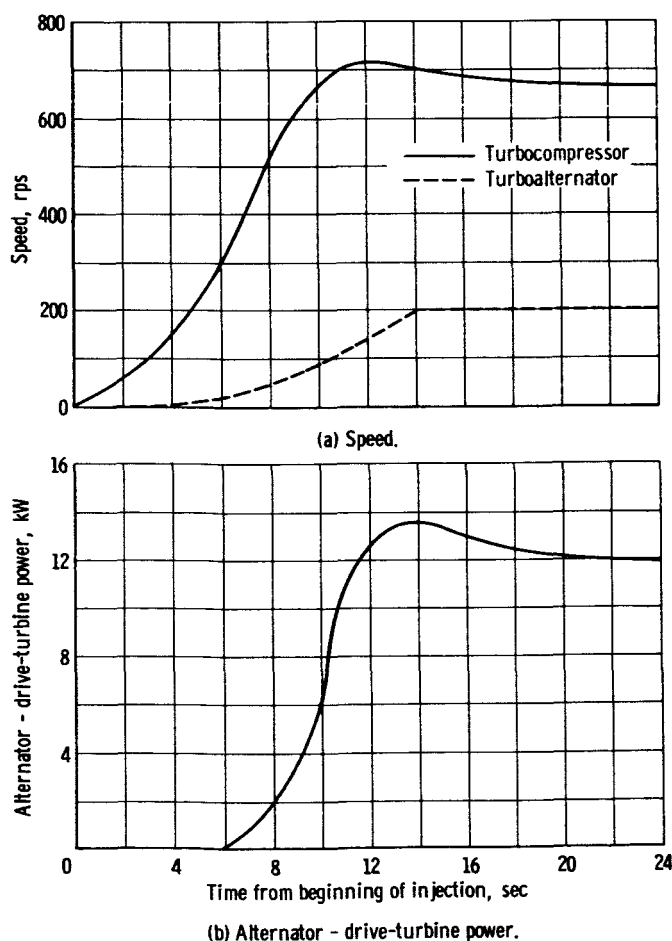(b) Alternator - drive-turbine power.

Figure 13. - Accelerations of turbomachines in startup. Gas injected at recuperator inlet (cold side) with check valve between injection point and compressor discharge. Gas flow, 10 percent of design value; initial radiator temperature, 480° R.

in which startup will occur. The sequence begins with the orientation of the collector at the start of the sun period in order to melt the lithium fluoride. The gas system startup must not occur before 6.5 minutes of sun time have elapsed; if it does, the net input power to the absorber will be insufficient to melt the lithium fluoride completely. The gas system startup, however, must be accomplished before 23 minutes of sun time, unless either collector misorientation or adequate absorber-radiation area is used for overtemperature protection. As mentioned previously, the door area for radiation must be about 7 square feet if the gas system power is zero.

For the second sequence, it is assumed that the lithium fluoride enters the sun period in which startup occurs in a fully melted condition. The gas system is started at the beginning of the sun period without collector orientation. The collector orientation must be achieved before 21 minutes of sun time have elapsed in order to allow the absorber to enter the shade region in a fully melted condition. With this method, startup imposes no special requirement regarding absorber overtemperature protection, since the collector is oriented after the gas system is started. Protection against the power excess at near-design operation, however, is still required (door area, 2.4 sq ft).

CONCLUSIONS

The conclusions of an investigation of control and startup requirements for the two-spool solar Brayton system in a 300-nautical-mile ecliptic Earth orbit can be summarized as follows:

1. Variations in alternator - drive-turbine power above the design value due to orbital reductions in radiator sink temperature and reasonable overdesign values of gas inventory are small and can be readily accommodated in the speed control design. Even with design margin between alternator - drive-turbine power and maximum expected load, an alternator overload control should be provided. With such a control, design speed of the turboalternator can be maintained even if substantial reductions occur in collector power.

2. The variations expected in turbocompressor speed are small and require no speed control of this unit.

3. Increases in absorber output power because of shade radiator operation or high gas inventory are small and should not be a problem in regard to premature freezing of the lithium fluoride with the small margin logically provided in matching the gas system to the collector-absorber combination. A small margin, however, will not accommodate much reduction in collector power from the design value. With reduced collector power and, hence, lithium fluoride temperatures below the melting value in the shade period, system output power cycled during the orbit and reached values considerably below de-

sign. A more favorable power cycle for some missions may be gained with a simple on-off·absorber-output power control by using a bypass from compressor outlet to inlet. A modulated constant output from the system can be provided most efficiently by a continuous control by using inventory adjustment. This method can be used for collector powers reduced by approximately 25 percent of design.

4. In order to provide for collector power above the design value or for reduced absorber output power caused by gas system variations, such as below-design inventory, an absorber overtemperature control is needed. The design margin discussed in item 3, of course, accentuates this need. This control can be accomplished with absorber doors for radiation.

5. With the large volume of the gas flow radiator, gas injection startup can be accomplished without a vent-to-space valve and, when the injection point is the compressor - drive-turbine inlet, without a flow-directing check valve. For turbine inlet injection, however, the temperature of the injected gas must be at least 1250° R; whereas, cold gas is sufficient if it is injected at the recuperator inlet (cold side) and directed through the hot absorber by use of a check valve.

6. Excessive absorber-output powers occur in the startup transient when the initial temperature of the radiator metal is substantially below the design value. This requires the parasitic load of the turboalternator speed control to be oversized and also requires the startup to take place during special periods of the orbit. Two sequences satisfying this latter requirement were determined. One sequence is for an initial condition where the lithium fluoride is frozen, but at the melting temperature, and the other sequence begins with a condition of completely molten lithium fluoride.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, May 27, 1966,
123-33-04-03-22.

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